Ősz Olivér

Methods for scheduling industrial processes

Módszerek ipari folyamatok ütemezésére

Theses booklet

Doktori tézisek

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Introduction

Scheduling is a research field under operations research that deals with optimization problems containing timing-related decisions. As time is an important aspect in our life, scheduling problems arise in lots of vastly different areas. Some examples are timetabling, CPU scheduling, supply-chain management, project planning, and production scheduling. My research is focused on the latter, the scheduling of industrial processes in manufacturing systems, with possible applications of the methods in logistics and project planning as well.

As in all optimization problems, the goal is to find the best solution among a lot of possible alternatives. In scheduling, the solution is a schedule, which contains decisions about the timing of events, and other related values, such as resource allocations, transportation paths, and material quantities. The quality of the solution is defined by the objective function, which assigns a numerical value to each solution. The goal is to find the solution with the lowest or largest such value, depending on whether it is a minimization or maximization problem. The most often occurring objective is to minimize the maximum completion time over a set of processes. Other examples for objectives are minimization of operation costs, investment costs, delay, or maximization of hourly profit.

The research problems in scheduling research are to create efficient solution algorithms for finding optimal, or near-optimal solutions for scheduling problems. As even fairly simple scheduling problems have NP-hard complexity, exact solution approaches guaranteeing optimality have exponentially increasing execution times in relation to problem sizes. For this reason, heuristic approaches are also actively researched, which are not guaranteed to find the globally optimal solution but can quickly obtain good solutions even for large problems. My research is concentrated on exact solution methods because as computational power is increasing and the algorithms are improving, more and more practical problems can be solved to optimality in reasonable execution times. Furthermore, exact and heuristic methods are often used in combination, so it is important to research improvements to both approaches. Also, most exact algorithms can be stopped to provide the best found solution even before proven optimality is reached, and an upper bound on the deviation from the optimal solution is known.

During my research, I investigated several problem classes and different solution techniques. Some of the problems come from theoretical classifications that apply to a wide range of scheduling problems, while others come from case studies of specific application areas. This work contains both types of problems.

Scheduling has a vast literature, and there are already numerous known problems and solution approaches, although there is still a lot of room for further research. My research has multiple motivations:

- Identify new problem classes in practice that have not been investigated in the literature, and propose solution methods for them.

- Extend the capabilities of existing solution methods, so they can be applied to a more general problem class.

- Improve the performance of existing solution approaches.

Theses

Thesis 1

Thesis statement 1 *I have developed improvements to existing MILP models for scheduling automated wet-etch stations and other automated manufacturing systems, accelerating the more general model by orders of magnitude, and extending the solvable problem class of the more specialized model.*

Thesis statement 1/a *I have improved the performance of the model by Aguirre et al. (2013) by developing new constraints for modeling empty robot movement without requiring immediate precedence variables.*

Thesis statement 1/b *I have extended the model by Castro et al. (2012) to be able to handle empty robot movements, robot zones, limited wait times, and flexible transfer times, and validated its correctness on literature problem instances.*

My publications related to the statement: [1] and presentations [2, 3]

Automated wet-etch stations require strict scheduling to avoid damaging the semiconductor wafers in chemical baths. Transporting robots are used to ensure precise timing throughout the process. Such robots are becoming more popular in other manufacturing systems as well. Modeling the travel times of these robots required new constraints, and it is difficult to formulate them in an efficient and accurate way. I managed to improve the solution performance and correctness of existing models by providing new formulations.

Thesis 2

Thesis statement 2 *I have extended the S-graph framework with new branching algorithms and modeling methods to solve the RCPSP with single or multiple modes per task, and with constant or piecewise linear time-varying resource capacities.*

Thesis statement 2/a *I have formulated Constraint Programming models to generate minimal resource incompatible sets of tasks or task-mode pairs for single- or multi-mode RCPSPs.*

Thesis statement 2/b *I have developed branching methods for the S-graph based solution of the single- and multi-mode variants of the RCPSP, which can be used to partition the search space by resolving incompatible and infeasible sets.*

Thesis statement 2/c *I have extended the S-graph model with virtual tasks to represent resource disruptions at fixed time intervals.*

My publications related to the statement: [4] and presentations [5, 6]

The Resource-Constrained Project Scheduling Problem (RCPSP) studied mostly in project management is a more general problem than most industrial scheduling problems. It requires the scheduling of processes that may use multiple scarce resources at the same time. Such processes can also be found in manufacturing systems, so it is useful to extend existing scheduling methods, such as the S-graph framework, to this problem class. Although there are other techniques for solving the RCPSP, the S-graph methodology has some advantages over other approaches, such as correct modeling of No Intermediate Storage scenarios, or providing multiple alternative solutions.

Thesis 3

Thesis statement 3 *I have identified and defined a scheduling problem with novel features at an axle-manufacturing system, and developed a discrete-time MILP model that can solve it.*

Thesis statement 3/a *I proposed 4 additional constraints to tighten the formulation, and compared their impacts on solution performance with randomly generated test cases.*

My publications related to the statement: [7] and presentation [8]

While there are many different scheduling problems in the literature, real world applications will always provide new challenges that require new methods, or at least modifications to existing models. In this case, the lifetime deterioration of the forging dies used for forming heavy-duty axles was caused by changing and setting up dies between processing different products. This creates a tradeoff between minimizing the changeovers to utilize the dies better, and completing orders for more different product types. I created a MILP model for this problem by applying different modeling techniques known from literature approaches and coming up with new techniques as well.

Thesis 4

Thesis statement 4 *I have developed a solution approach based on the S-graph framework for scheduling batch processes with the objective of freshwater usage minimization through wastewater recycling, and validated it on literature examples.*

Thesis statement 4/a *I have extended the S-graph model to store decisions about reusing the output water of a task as input water for other tasks.*

Thesis statement 4/b *I have modified the equipment-based branching method of the S-graph framework to generate partial schedules with alternative water usage decisions subject to contamination constraints, and to introduce the necessary precedence relations between the affected tasks.*

My publication related to the statement: [9]

One way to minimize freshwater usage of manufacturing processes is to reuse the water coming from one stage at another stage, mixing it with freshwater if necessary. This approach can be more effective if decisions about these internal water flows are made at the scheduling level, not only after the schedule is fixed. This requires the extension of existing scheduling methods with new types of decisions, constraints, and objectives. Literature approaches used MILP models to integrate water minimization into scheduling. The S-graph framework has been used successfully for several scheduling problems, and provides different modeling possibilities than MILP models, which motivated me to extend its branching procedure with water flow decisions and its bound function for water usage minimization.

Conclusions

I studied several very different scheduling problems and solution approaches. Most practical applications require specific modeling considerations, leading to even more types of problems and needs for research efforts in finding adequate solution methods for them. It is clear that scheduling is a hard problem, so the process of improving existing approaches will continue in the foreseeable future.

In Thesis 1, I presented improved methods for scheduling automated manufacturing systems. This research topic is getting more and more attention, as automation levels rise throughout many industrial sectors. Future research can further improve the efficiency of these systems through cyclic scheduling, and online, reactive scheduling based on real-time data received from IoT sensors.

In Thesis 2, I proposed an S-graph-based solution method for the RCPSP. Extending other existing machine scheduling, batch process scheduling, or other solution approaches to this problem class is a promising topic for future research.

In Thesis 3, I presented and solved a problem from the steel-processing industry with problem-specific constraints that have not yet been addressed by scheduling methods. Despite the specific nature of this problem, the deterioration of production tools is apparent in many industries, so my presented approach may be used in other fields as well.

Integrating water minimization into scheduling, which I presented in Thesis 4 through an extension of the S-graph framework, and considering other environmental impacts of the production systems is an important aspect that needs more attention in scheduling and production planning. I am happy to see that this is already happening, and that I could contribute to this trend.

My publications referenced in the theses

[1] M. Hegyháti et al. "Scheduling of Automated Wet-Etch Stations". In: *Chemical Engineering Transactions* 39 (2014), pp. 433–438. DOI: 10.3303/CET1439073.

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My other publications

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